

# The controlling influence of the radiation budget on precipitation

*It is very likely that ....heavy precipitation events will continue to become more frequent, IPCC FAR*

## Outline:

1. Energy balance and water vapor feedback and downward longwave radiation
2. Water vapor feedback and atmospheric radiative cooling
3. Cloud effects on the atmospheric radiation budget
4. The radiative controls of global precipitation - why frequency of heavy rain events will decrease but intensity increases
5. The character of precipitation and what we learn from Earth observations

Some of this material appears in recent papers (e.g. Stephens and Ellis, 2008) and other is in prep for 3 different publications



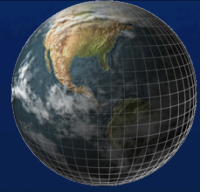
# A few complicating factors



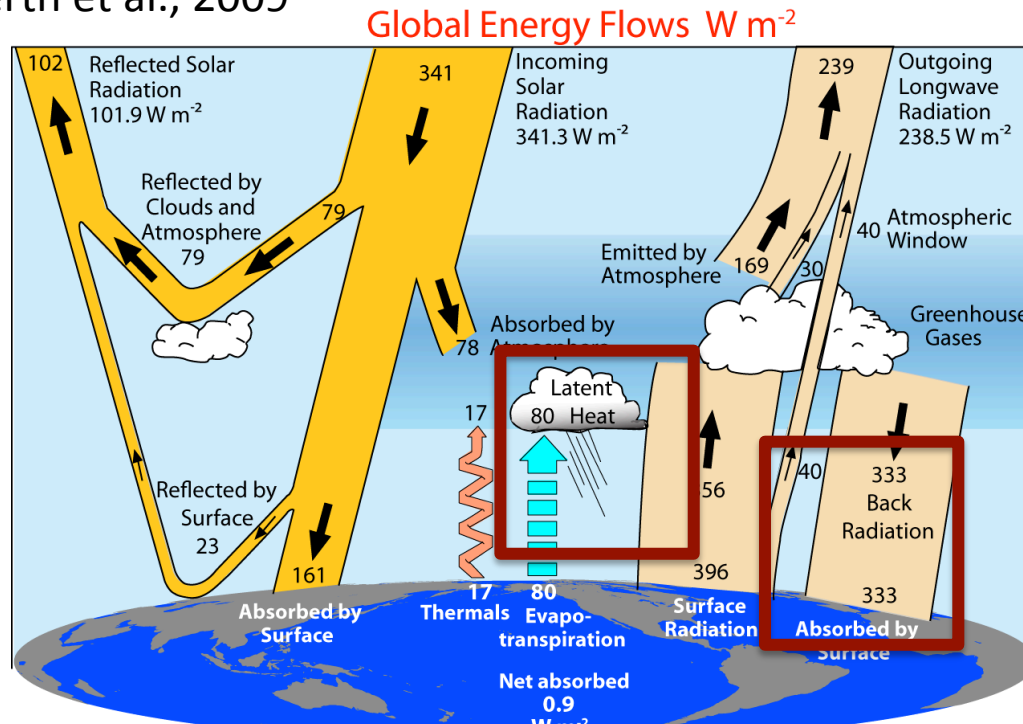
Water vapor feedback ‘.....*water vapor*, confessedly the greatest *thermal absorbent* in the atmosphere, is dependent on temperature for its amount, and if another agent, as CO<sub>2</sub>, not so dependent, raises the temperature of the surface, it calls into function a certain amount of water vapor which further absorbs heat, raises the temperature and calls forth for more vapor....’

Chamberlain’s correspondence to Abbot, 1905

# The Earth's energy balance



Trenberth et al., 2009



Cloud radiative effects  
TOA -20  $\text{W/m}^2$

$$R_{net,atm} = 78 + (396 - 333 - 239) = -98$$

*Almost balanced by LH*

There are a number of areas where this viewpoint is to be questioned (in my view)

**'Back' radiation** – changed from 323 to 333  $\text{W/m}^2$  but global estimates based on surface/satellite data are more like 345-355  $\text{W/m}^2$

**Solar in atmosphere absorption** – changed from 67 to 78  $\text{W/m}^2$  - the revision I think is too high over estimating effects of absorbing aerosol globally

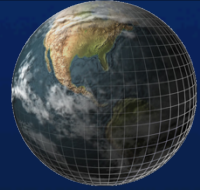
**Latent heating** - with perhaps 10-20  $\text{W/m}^2$  more radiant energy to the surface, this flux has to be much larger than given

	All Sky			Clear Sky		
	LW up	LW dn	LW net	LW up	LW dn	LW net
CERES SRBAVG-GEO						
Model A				397.6	313.1	-84.5
Model B	392	344.1	-47.9	391.4	313.5	-77.9
CERES SYN/AVG/ZAVG						
Untuned	397.9	342.2	-55.7	397.2	315.3	-81.9
Tuned	398.1	342.1	-56	398.1	315.2	-82.3
SRB						
GEWEX	397.1	342.9	-54.2	396.6	308.3	-82.3
QC	399.1	348.7	-52.4	392.2	313.3	-88.3
ISCCP	393.7	345.4	-48.3		313.9	
NCEP reanalysis						
	397.4	340.4	-57		312.7	
ERA-40	396.2	341.2	-55		314.1	-82.1
Trenberth et al (2009)	396	333	-63			
A-Train						
Radar (only)	394?	334	-60			
Radar+Lidar (RL)	399±7	358.8±7	-40±7		325.1	-73.9

In collaboration with Paul Stackhouse & Tristan L'Ecuyer

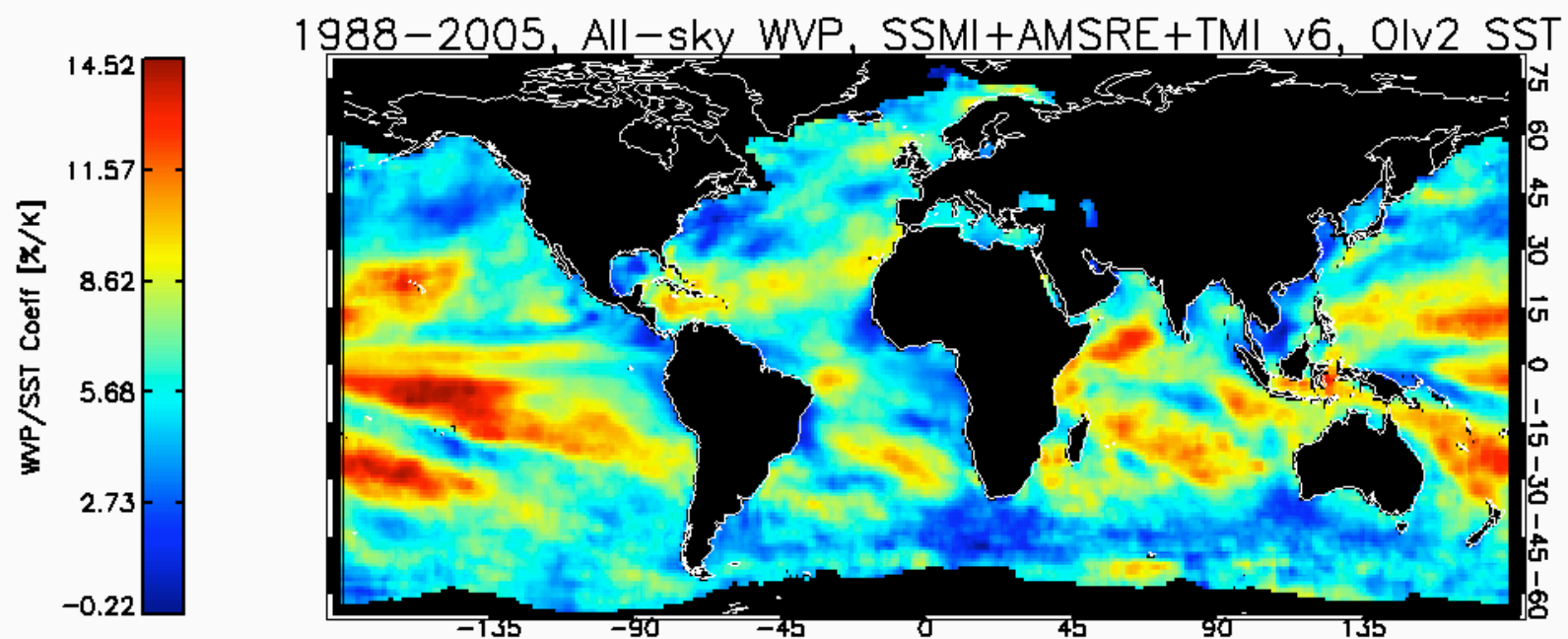
Cloud LW effects at surface, 26-36 Wm<sup>-2</sup>

*water vapor*, confessedly the greatest *thermal absorbent* in the atmosphere, is dependent on temperature for its amount

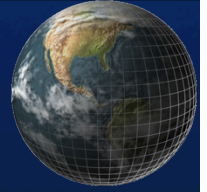


Observations from SSMI+TMI + AMSRE for the period 1988 -2005

Mean value 6.6 %/K



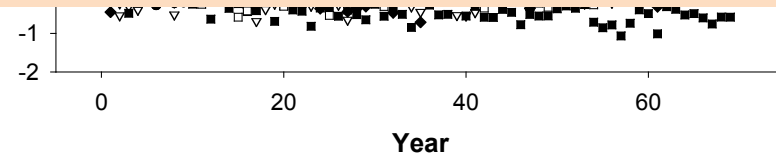
# DLR & Water vapor feedback (fixed RH, Manabe and Wetherald, 1967)



Thus fundamentally the driving force of surface warming in the feedback is the increase in DLR.....

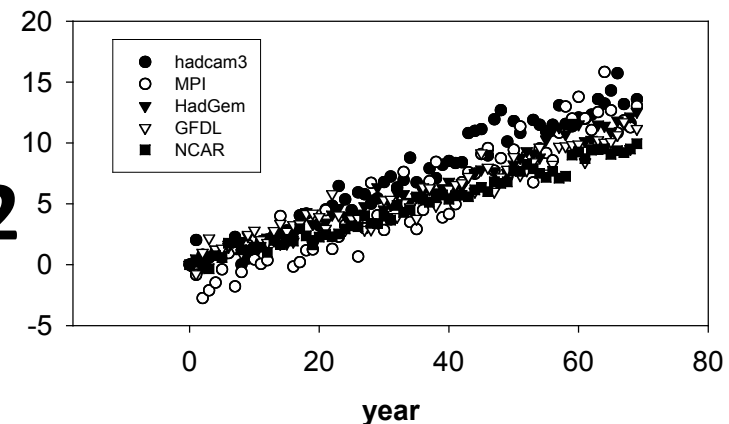
'it calls into function a certain amount of water vapor which further absorbs heat, raises the temperature and calls forth for more vapor'

**TOA**



IPCC 4<sup>th</sup> assessment

**Surface  
DLR, W/m²**



The increase in DLR is approximately equally split into temperature and water vapor contributions

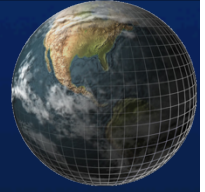
Change in Net LW at surface is primarily determined by change in column water vapor

Atmospheric model	$T_s$ <i>K</i>	Column water vapor <i>kgm<sup>-2</sup></i>	$\Delta DLR_{\Delta T}$ <i>Wm<sup>-2</sup></i>	$\Delta DLR_{\Delta T + \Delta q}$ <i>Wm<sup>-2</sup></i>	$\Delta F_{SFC}$ <i>Wm<sup>-2</sup></i>	$\Delta F_{net}$ <i>Wm<sup>-2</sup></i>
Tropical	300	41.2	4.7	10.1	6.1	-4.0
Mid-lat summer	294	29.3	4.2	9.0	5.8	-3.2
Mid-lat winter	272.2	8.6	3.1	4.6	4.6	0.0
Sub-arctic summer	287.0	20.8	3.7	7.3	5.4	-1.9
Sub-arctic winter	257.1	4.2	2.5	3.5	3.9	0.4

$\Delta T = 1 \text{ K}$

$\Delta T = 1 \text{ K}$   
 $\Delta q = 7\%$

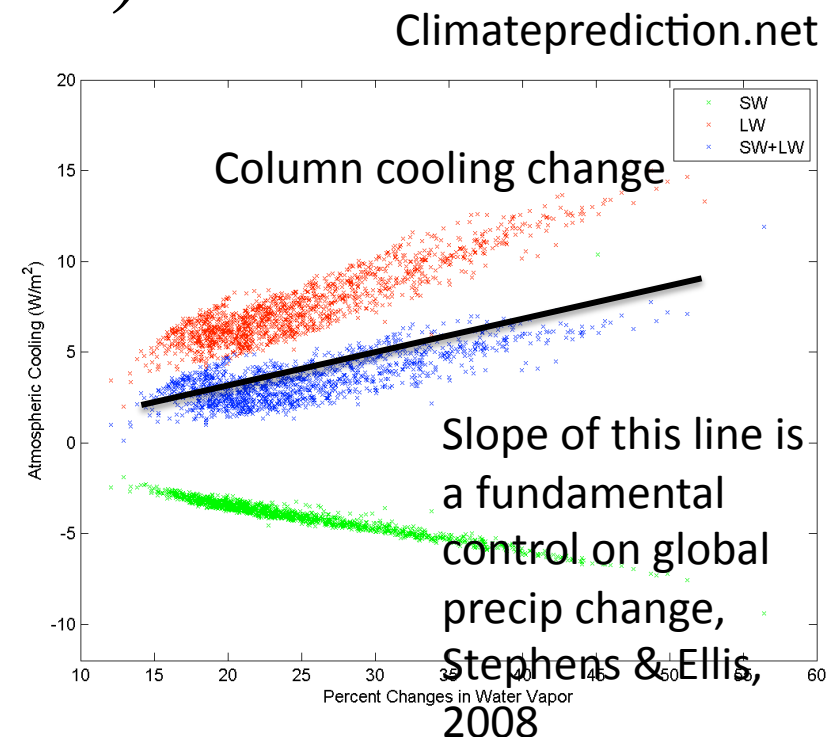
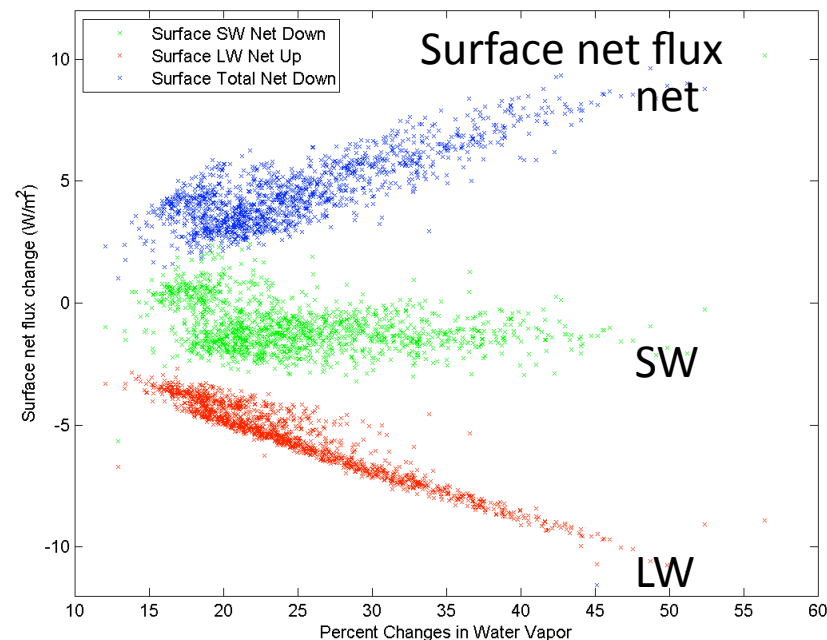
..... and a controlling influence on  
atmospheric net radiative heating/cooling



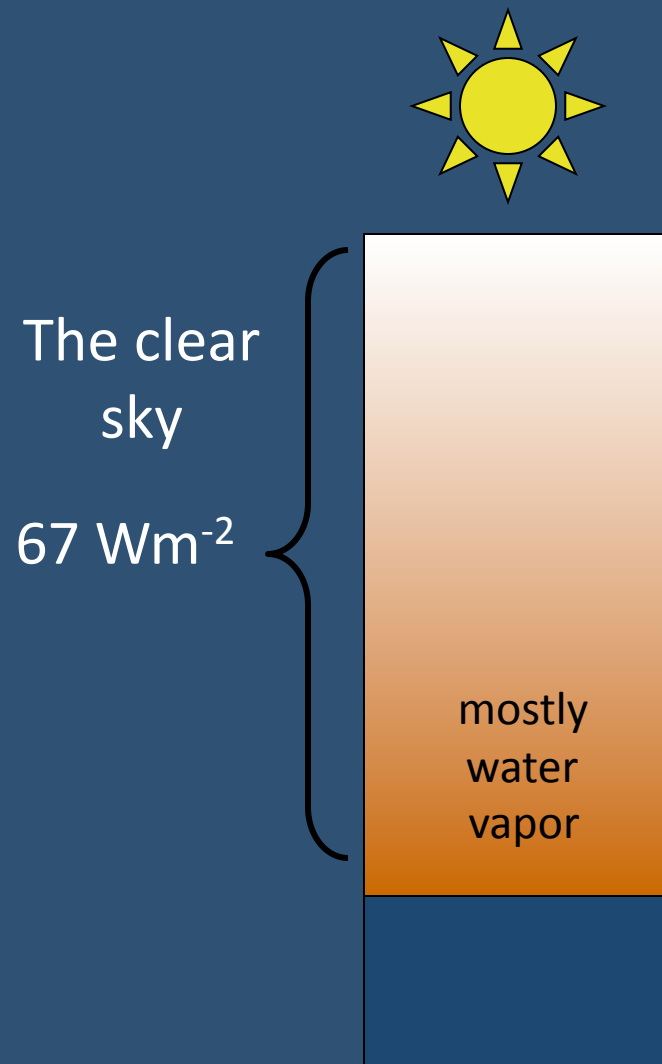
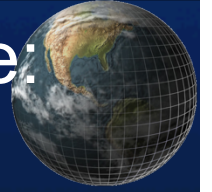
$$\Delta Q_{rad} = \Delta F_{net} - \Delta OLR$$

$$\Delta Q_{rad} = \Delta F_{net} - 0$$

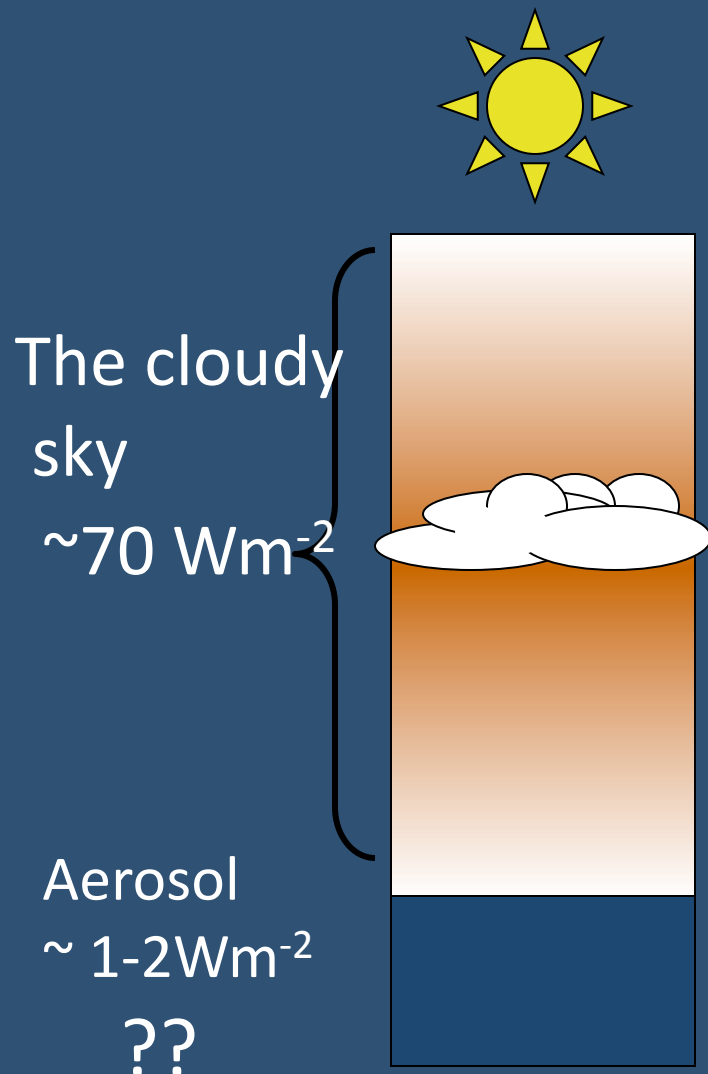
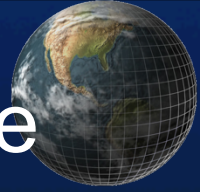
$$\Delta Q_{rad} = f(\Delta W)$$



# Clouds and the atmospheric radiation balance: a simplistic primer

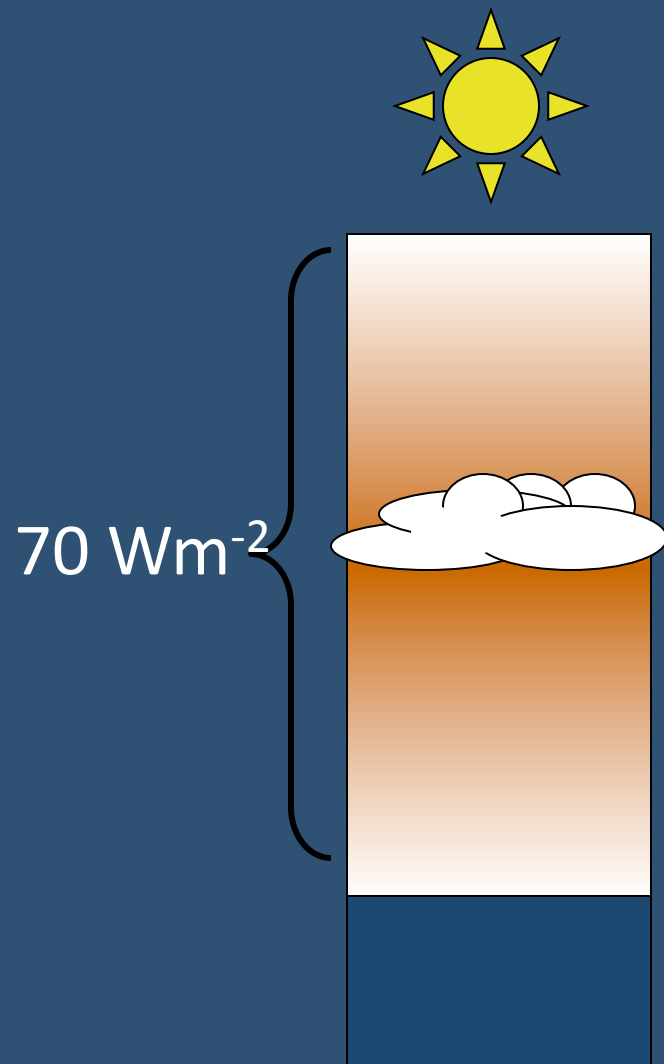
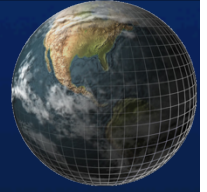


# Clouds and the Earth's energy balance

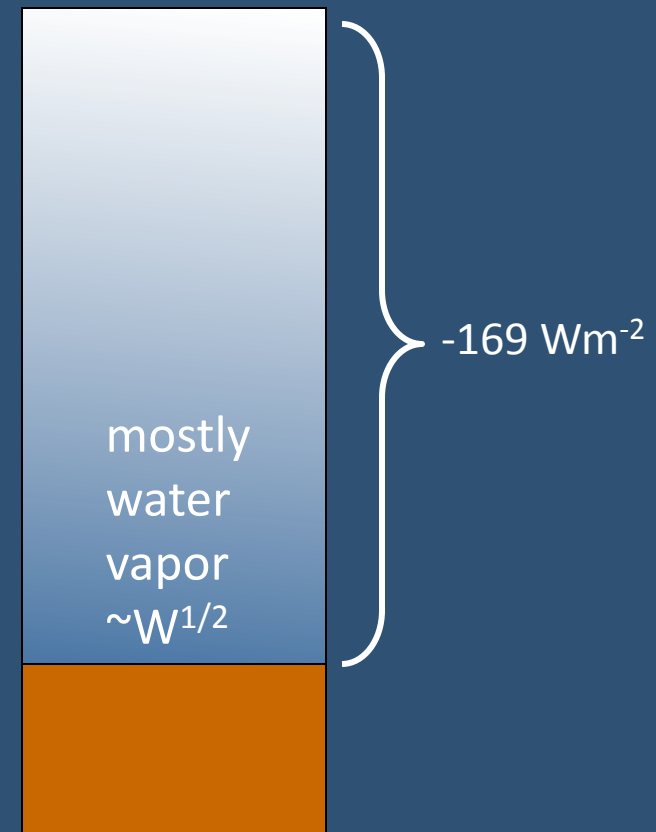


The introduction of clouds doesn't change significantly the column solar absorption but they do significantly redistribute the absorbed energy in the column

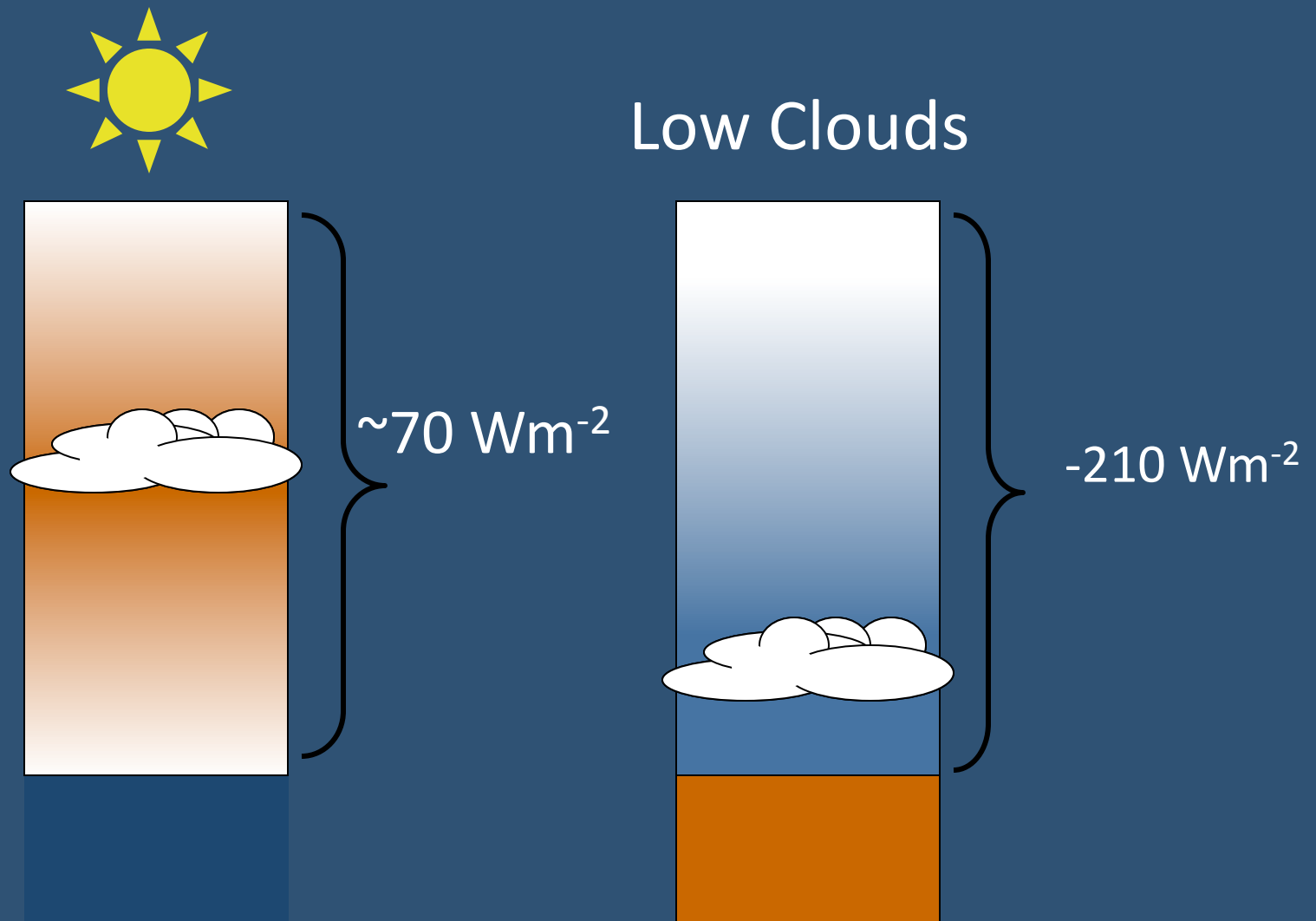
# Clouds and the Earth's energy balance



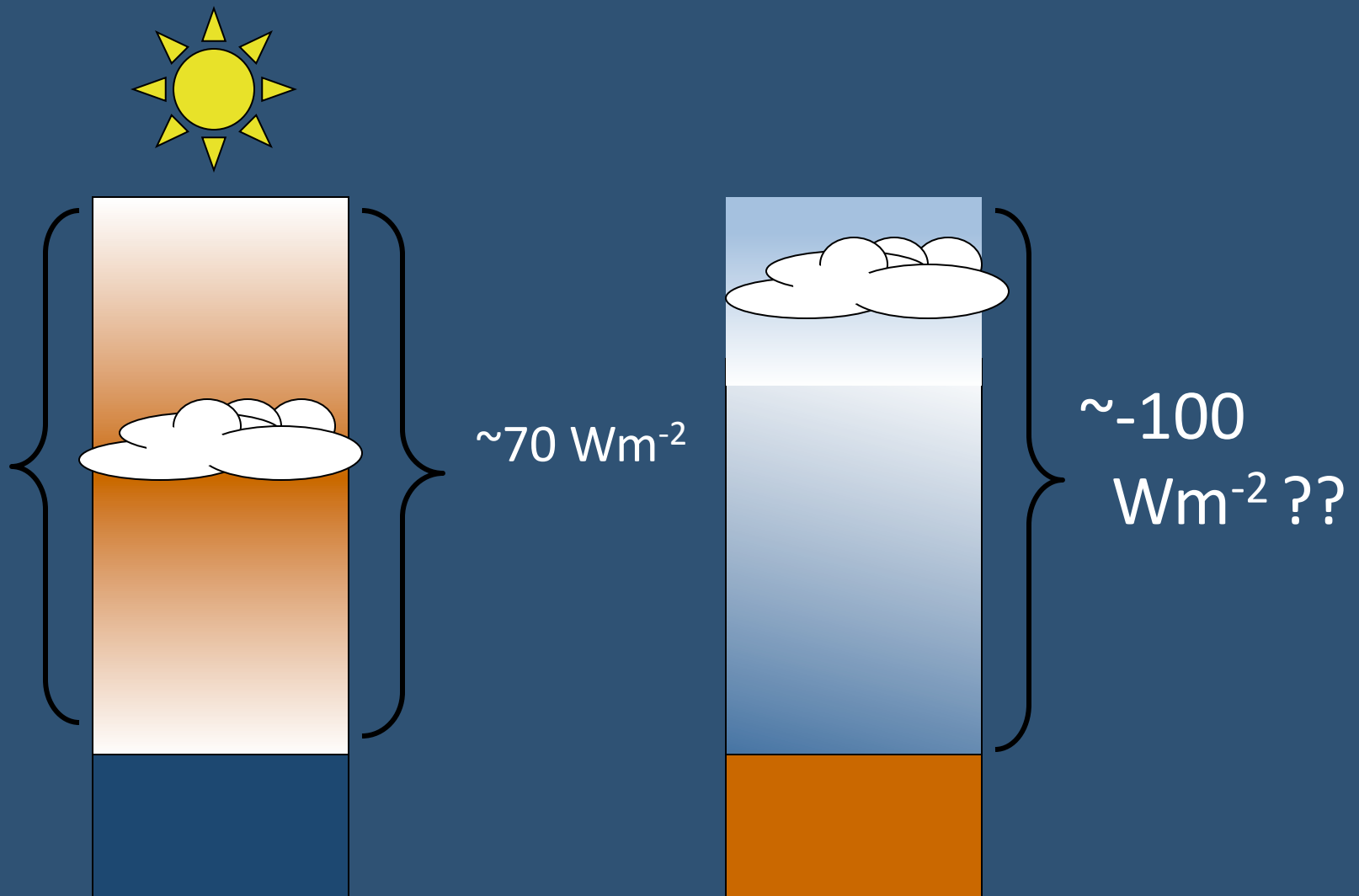
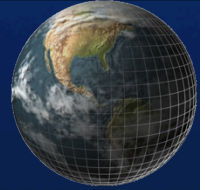
Clear sky  
longwave



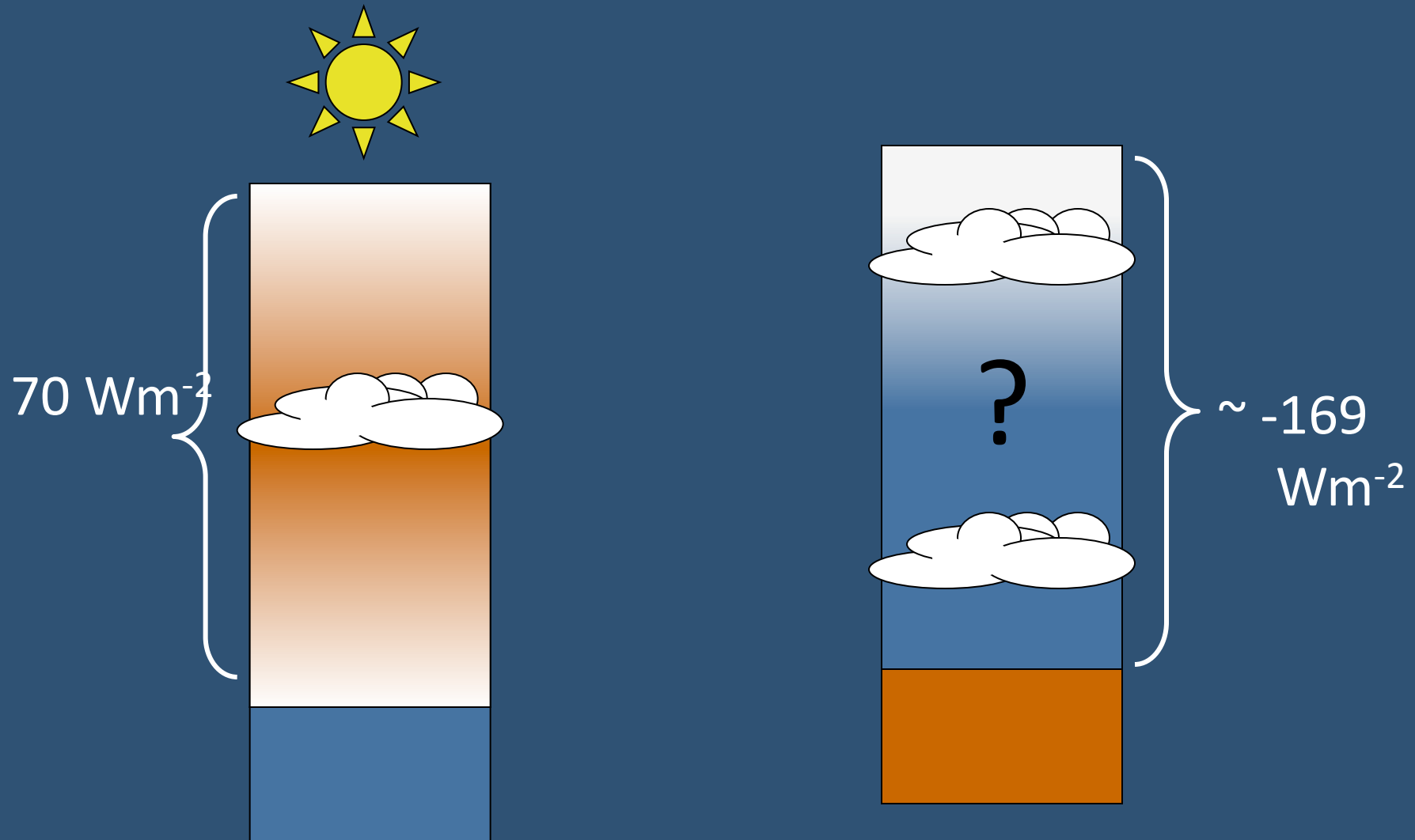
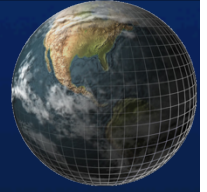
# Clouds and the Earth's energy balance

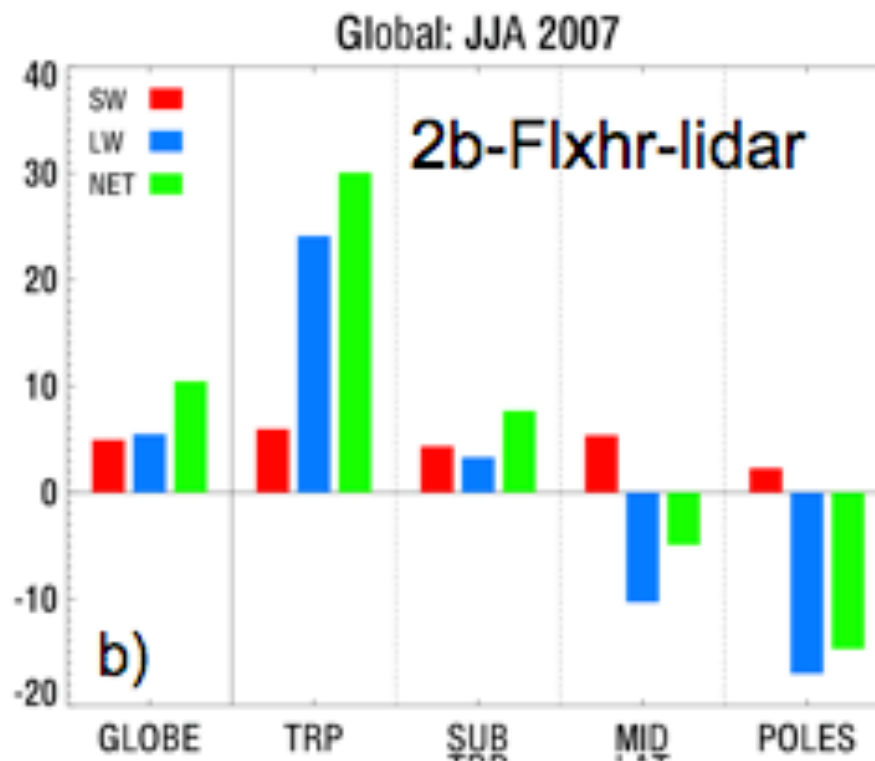
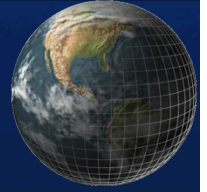


# The energy balance of the atmosphere

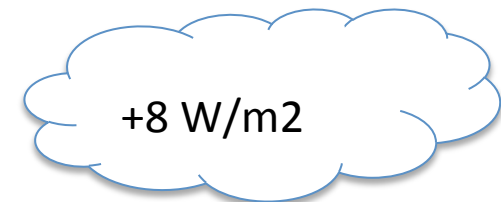


# The energy balance of the atmosphere





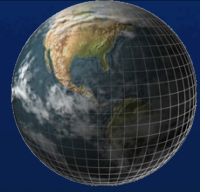
A-Train cloud-profile resolved data suggest that in the global mean, clouds heat the column by about



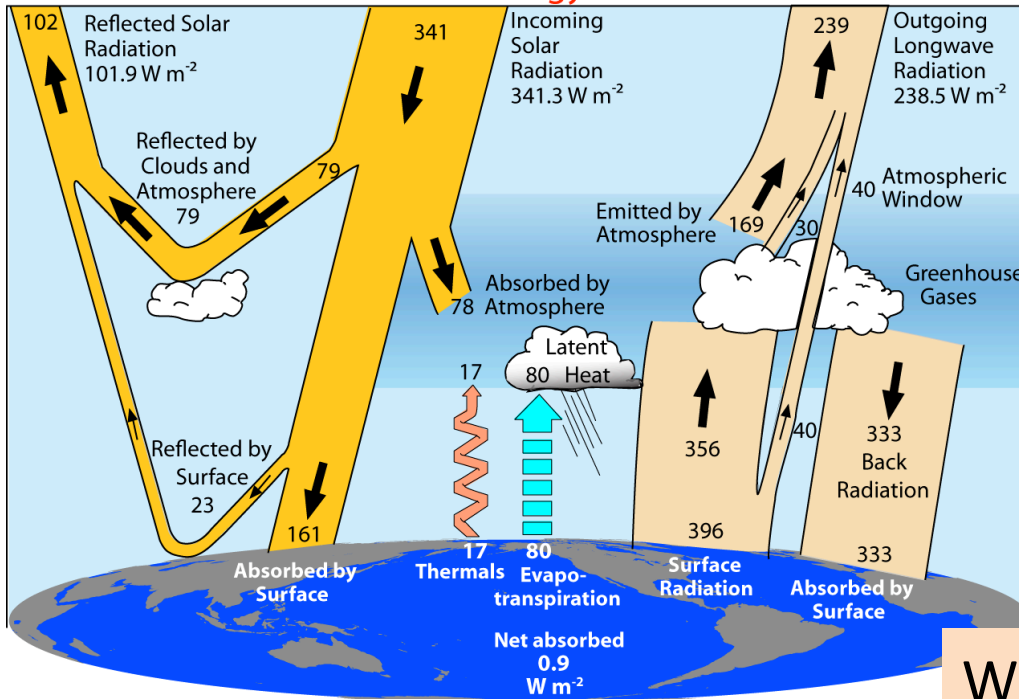
and this is dominated by long-wave contributions by tropical high clouds

Stephens et al., 2008

# The control on global accumulation



Global Energy Flows  $\text{W m}^{-2}$



Consider 'perturbed' state

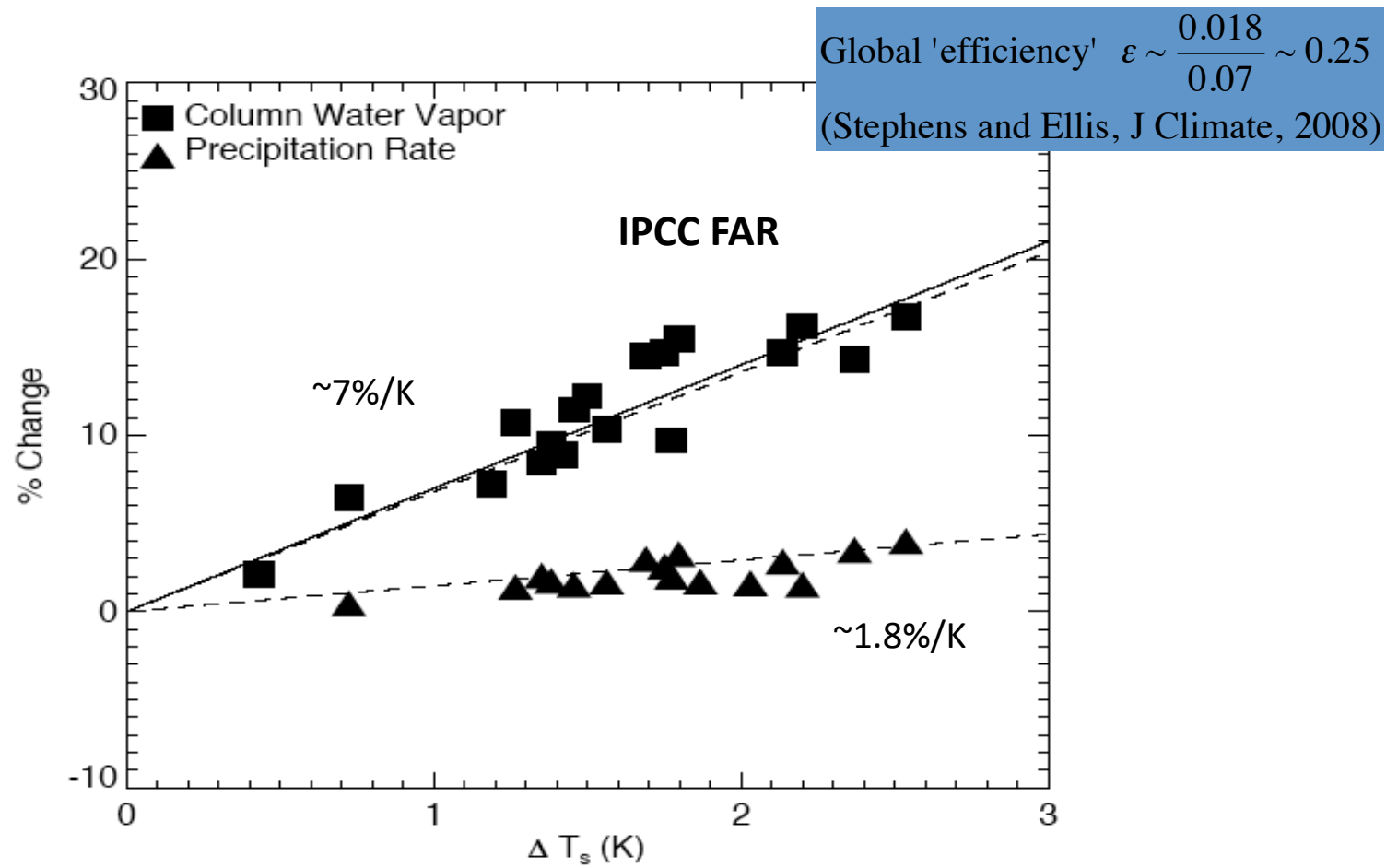
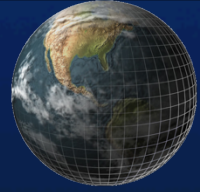
$$\Delta R_{net,atm} = L\Delta P + \Delta S$$

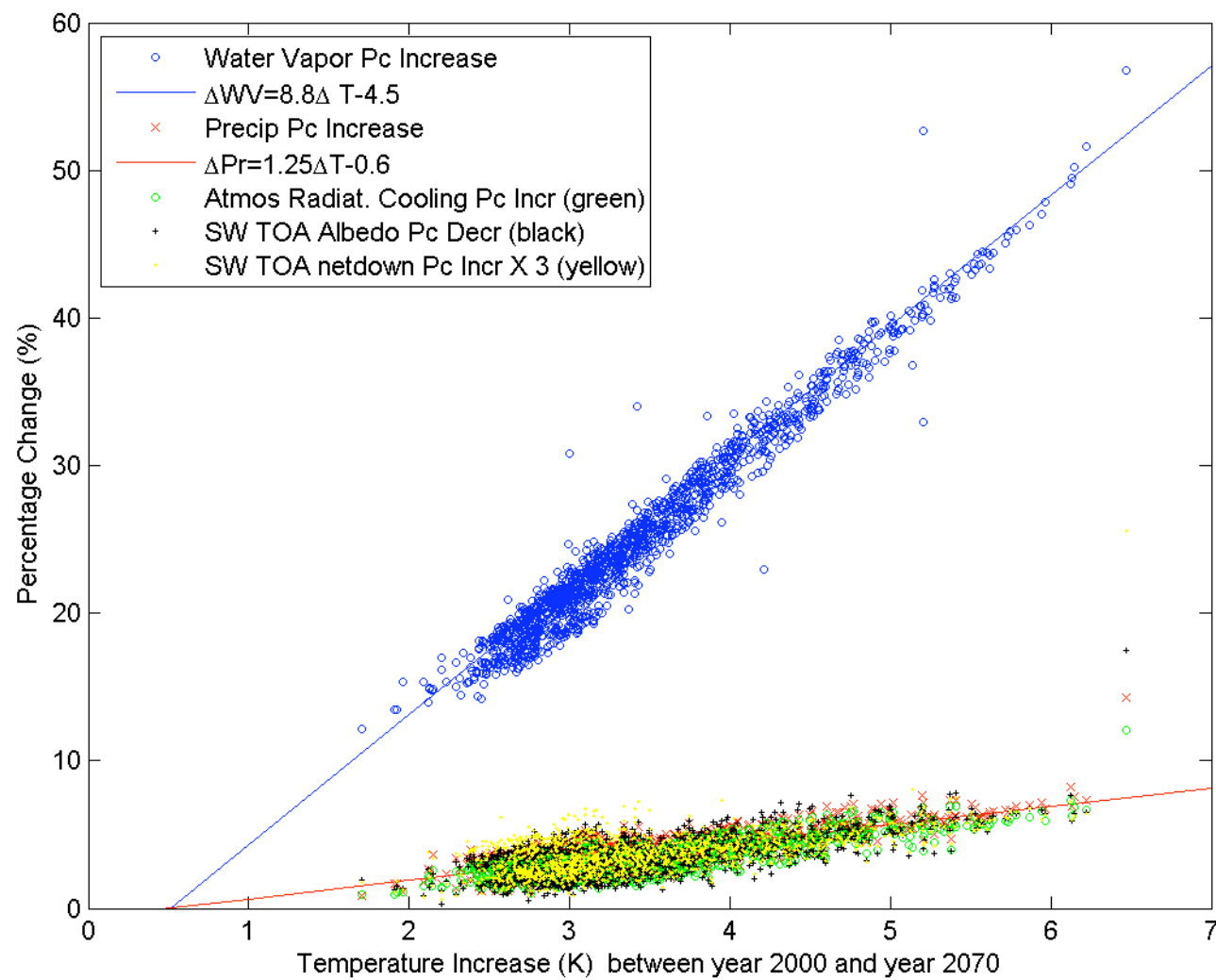
$$\Delta R_{net,atm} = \Delta R_{net,clr} - \Delta C_{net}$$

( $\sim 4 \text{ W/m}^2$ )      ( $\sim 1 \text{ W/m}^2$ )

$$\Delta R_{net,clr} \rightarrow \Delta W \text{ (water vapor)}$$

Water vapor change  $\sim 7\%/K$







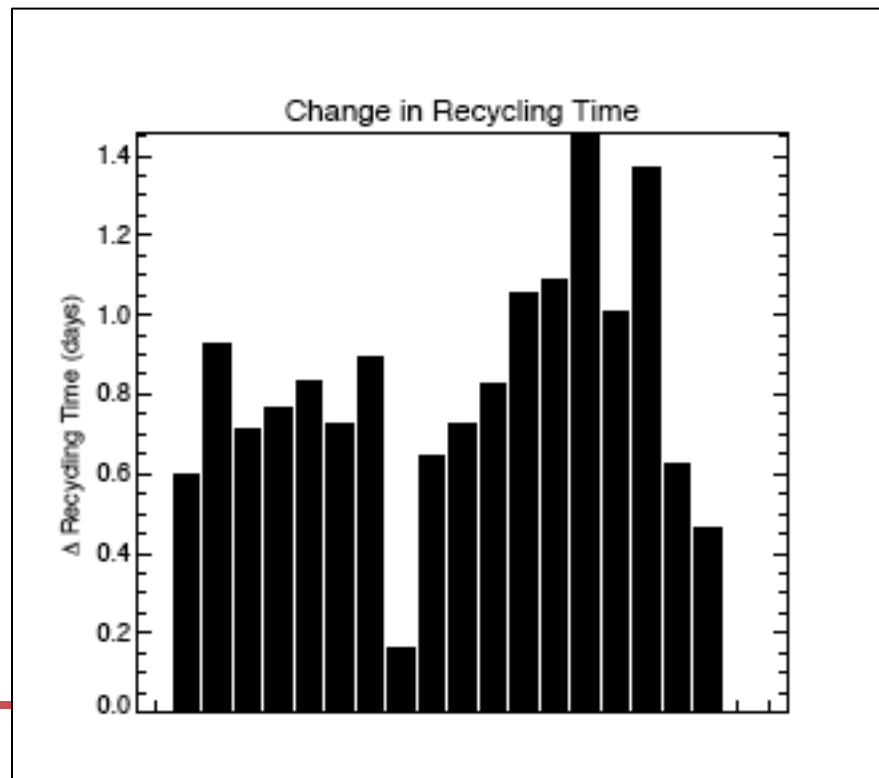
Simple expectations of water availability imply that the efficiency  $\sim 1$   
Why 2%/K ?????  
Models are clearly wrong!

**Scienceexpress** Report

**How Much More Rain Will Global Warming Bring?**

Frank J. Wentz,\* Lucrezia Ricciardulli, Kyle Hilburn, Carl Mears

The implication,  
water re-cycling time  
increases by about 1 day





$$\Delta R_{net,atm} = L\Delta P + \Delta S$$

$$\Delta R_{net,atm} = \Delta R_{net,clr} - \Delta C_{net}$$

for simplicity suppose

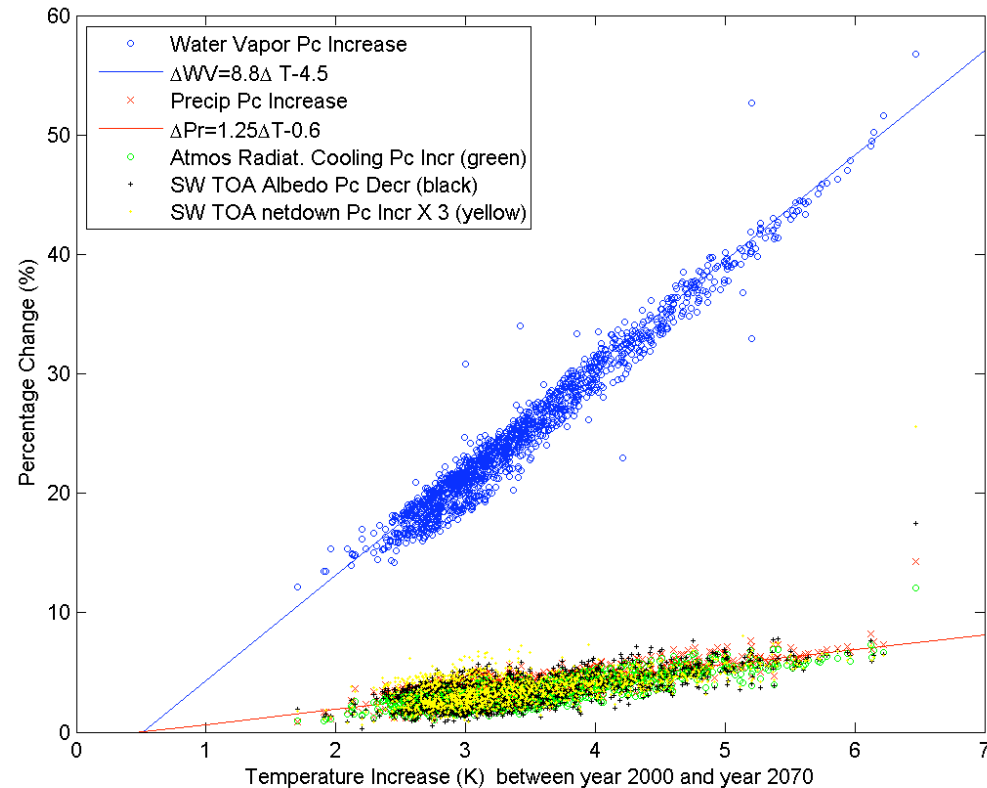
$$\Delta R_{net,clr} \sim L\Delta P$$

and

$$R_{net,clr} \sim aW^b$$

$$\frac{\Delta R_{net,clr}}{R_{net,clr}} \sim \frac{\Delta P}{P} \sim b \frac{\Delta W}{W}$$

$$b \sim 0.25 \dots$$



What about clouds, what about sensible heating?

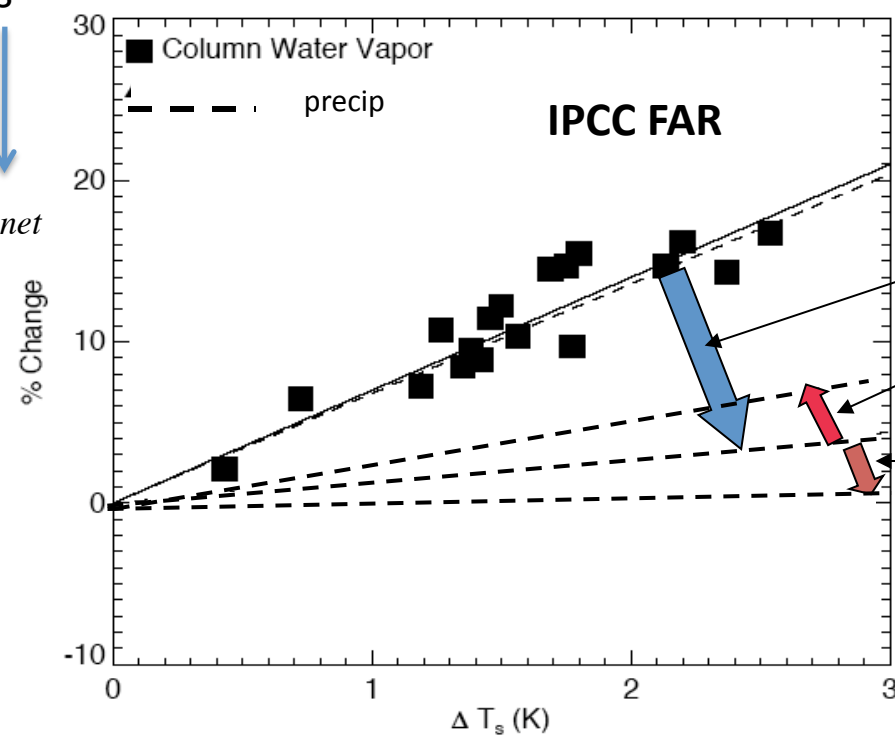
Climateprediction.net  
Yong Hu



## Changes in atmospheric CREs

$$\Delta R_{net,atm} = L\Delta P + \Delta S$$

$$\Delta R_{net,atm} = \Delta R_{net,clr} - \Delta C_{net}$$

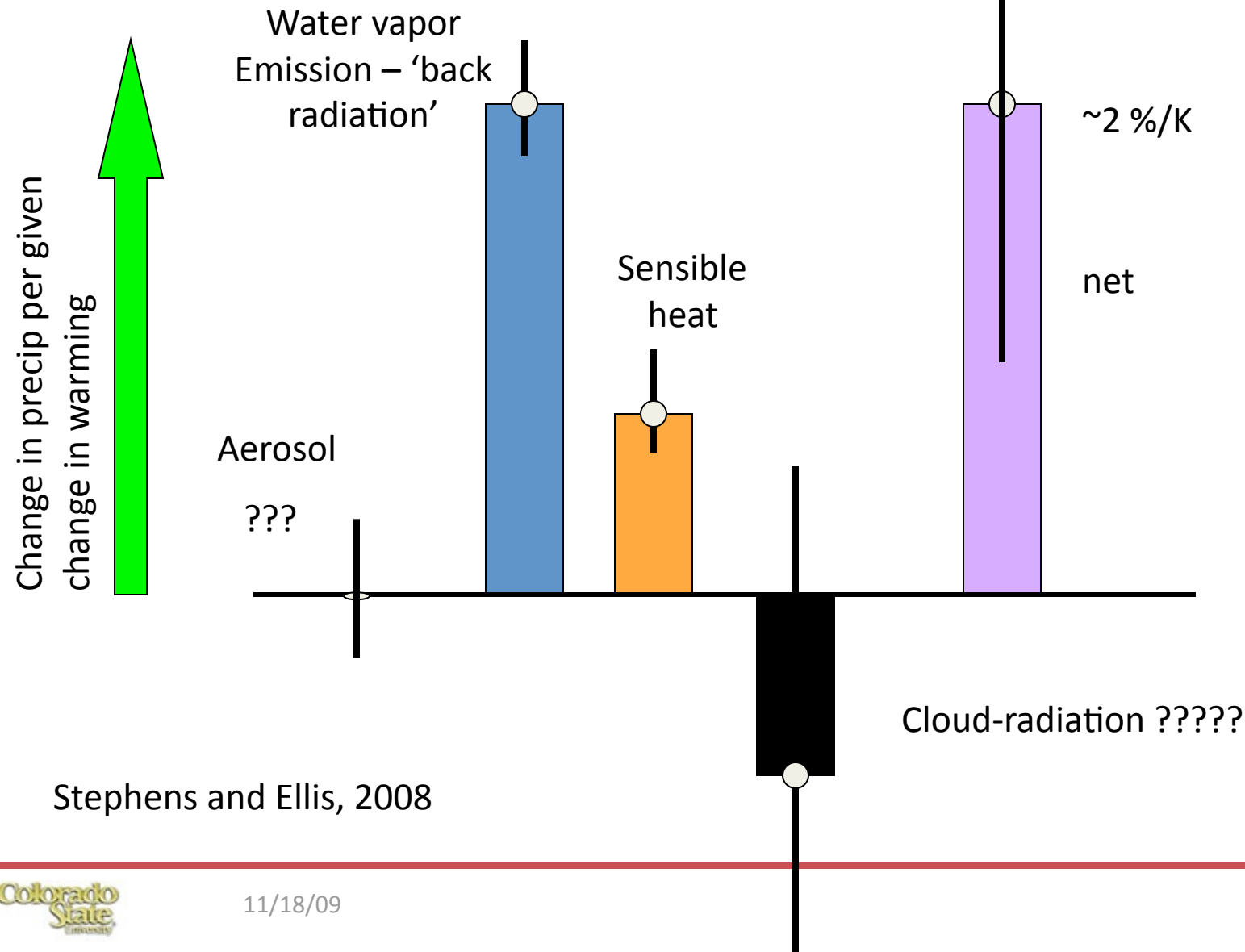
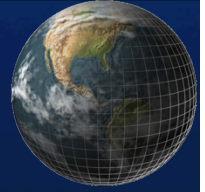


Curve of growth  $\Delta w$   
on  $\Delta R_{net,clr}$

Sensible heat  $\Delta S$  –  
controlled by water

Cloud radiative  
Effects  $\Delta C$  –  
heating change by  
high clouds

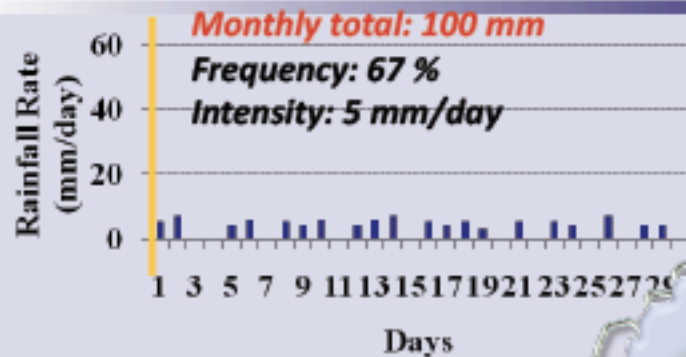
# Summary of global controlling factors



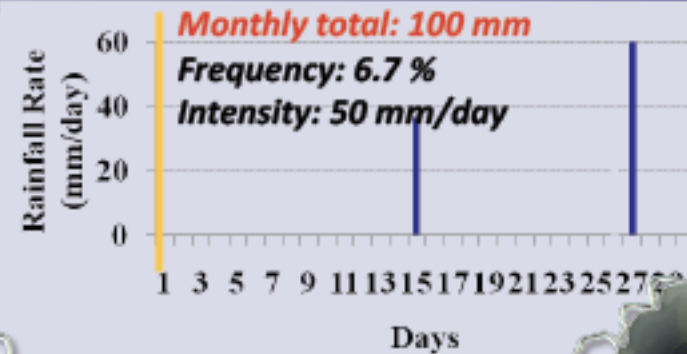
Stephens and Ellis, 2008

..... frequency and intensity matter as much as amount .....

## *Temporal Scale Importance: Daily Precip. at 2 stations*

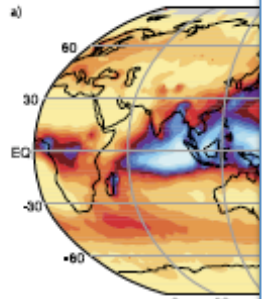
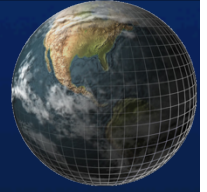


Soil moisture replenished  
Little run-off

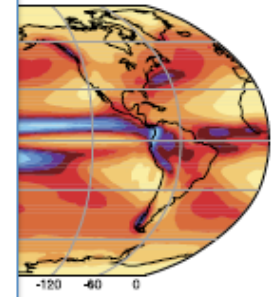


Localized flooding, stream bed  
recharge

### 3) The character of precipitation



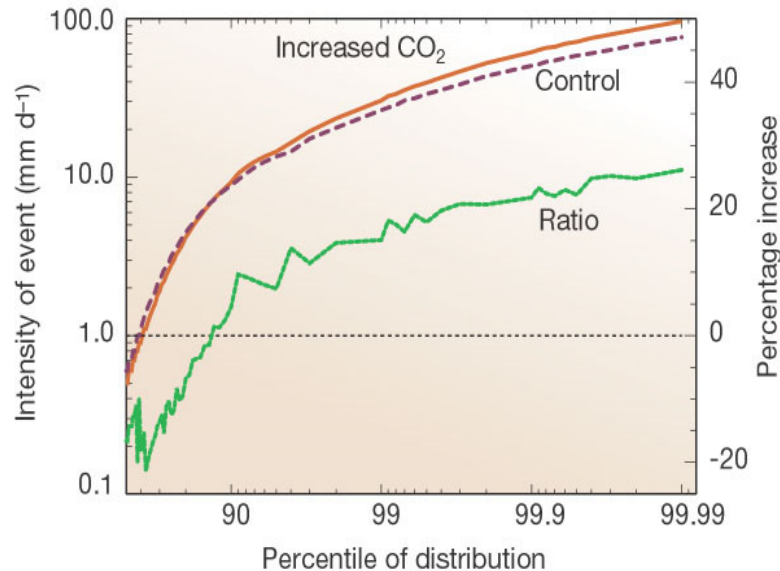
Annual or sea  
Observations



Model  
Intensity  
raining

But how would this increase be realized?

A model example - difference 2XCO<sub>2</sub>-1XCO<sub>2</sub>



**GCM CO<sub>2</sub> vs Control**

$\Delta T = 3.6K$  (2090s)

$\Delta P_{99.99} = 25\%$

$\Delta P_{99.99} / \Delta T \sim 7\%/K$   
C-C

Change in  
is globally  
atmospheric  
Precipitation  
increase

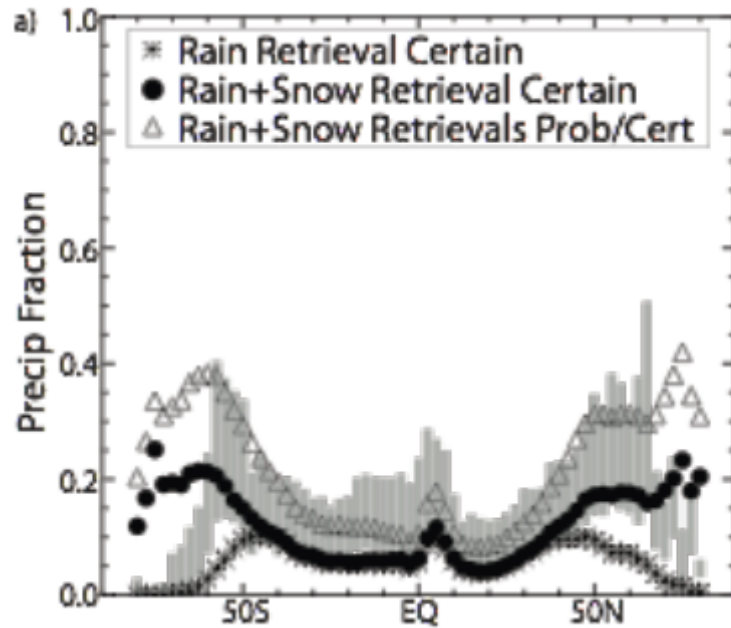
The pdf shifts from less frequent light to more frequent heavy rains and these appear to follow the rate of change of water supply (7%/K)

must  
s (?)  
increase

# The character of precipitation – what we are learning from these new Earth observations

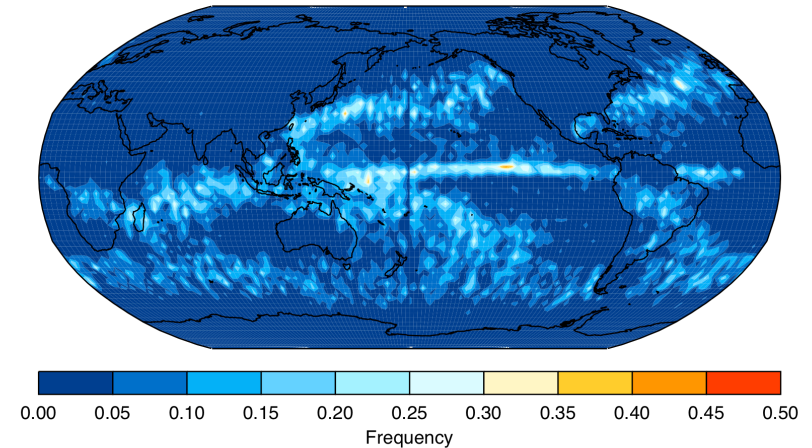
DJF, 2006/2007

Annual mean

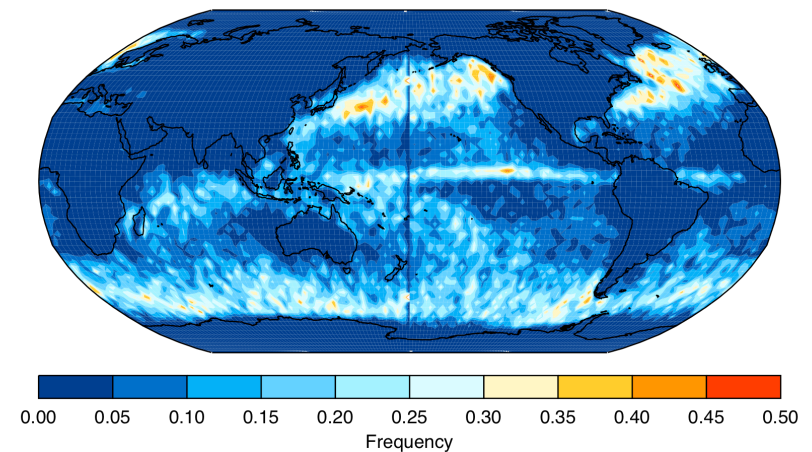


CloudSat incidence looks like COADS surface obs (Ellis et al. 2008) but other data (e.g. microwave radiometer products) don't (Petty, 1998)

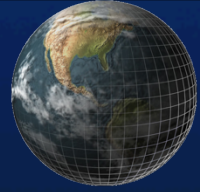
AMSR-E incidence 5%



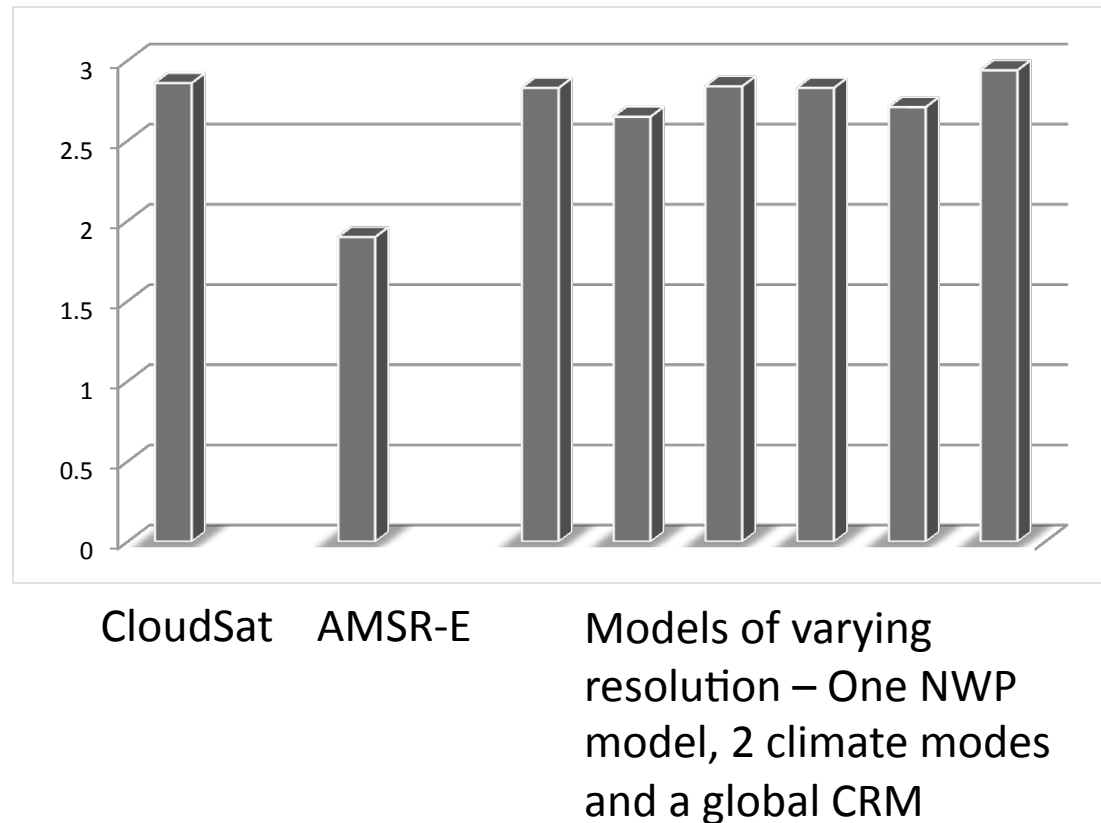
CloudSat incidence (11%)



# The character of precipitation – what we are learning from these new Earth observations

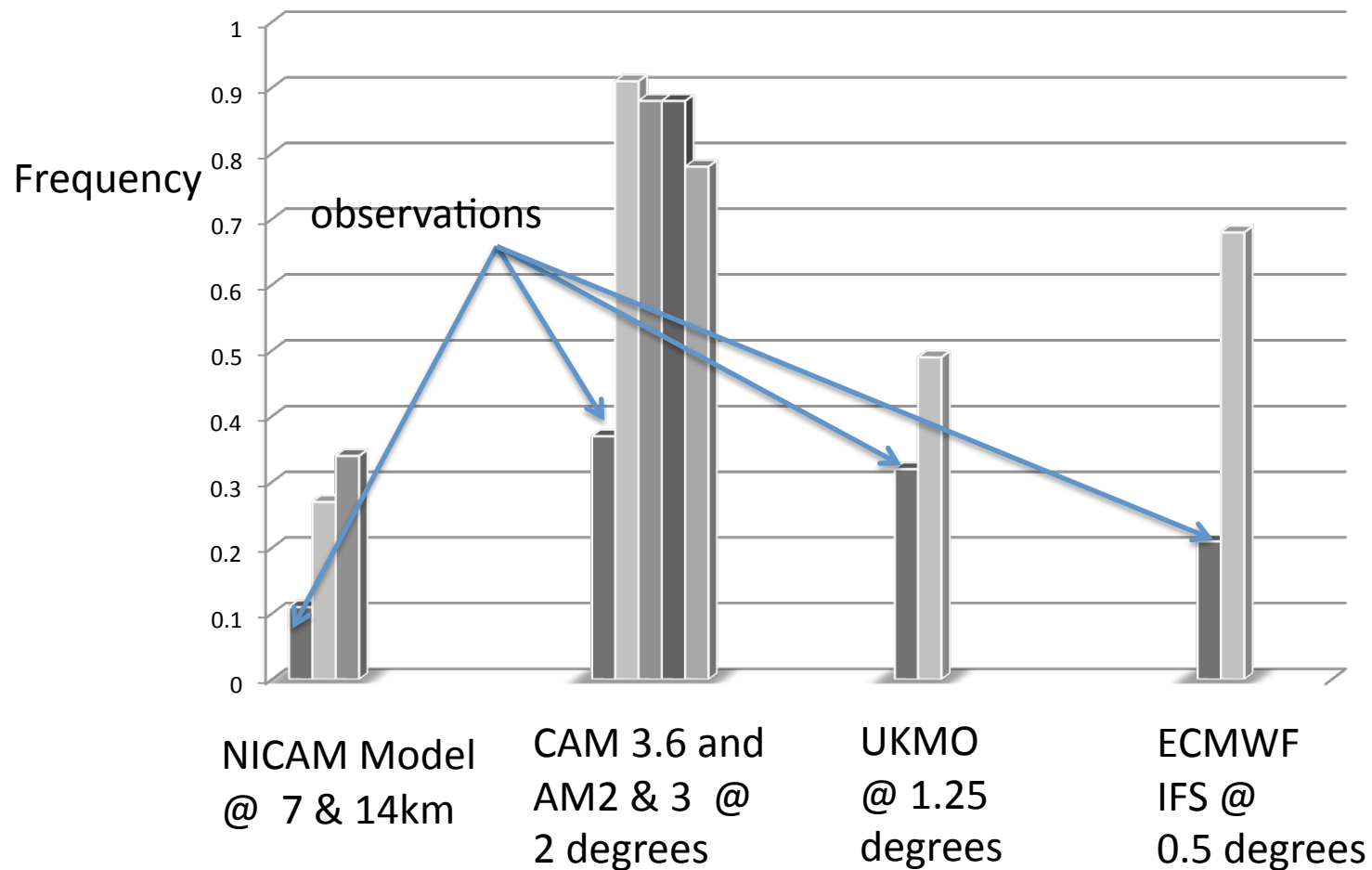
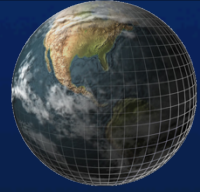


Annual  
Accumulation  
(mm/day)

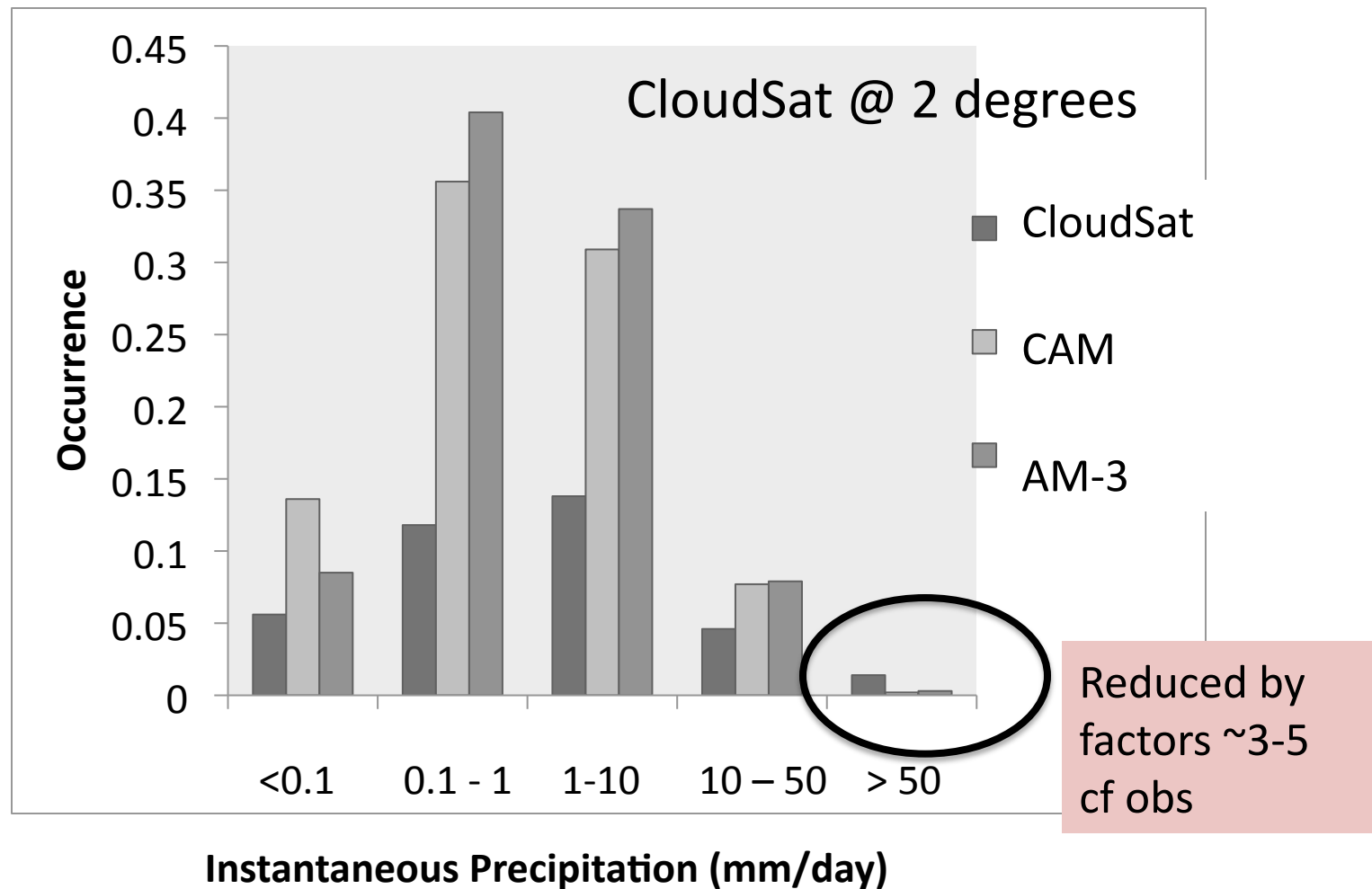
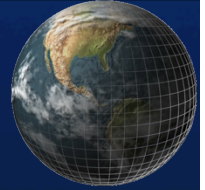


Model accumulation cannot be far from reality

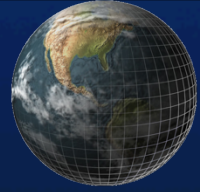
# Models produce rain 2-4 times too frequently regardless of resolution



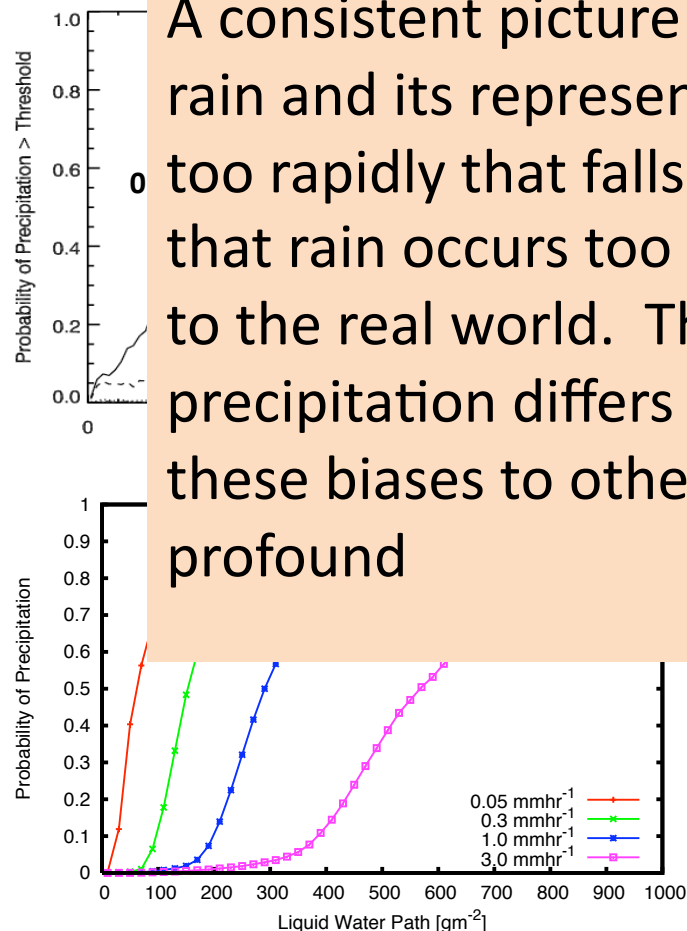
... and 2-3 times too light



# Probability of rain in warm clouds observations and models

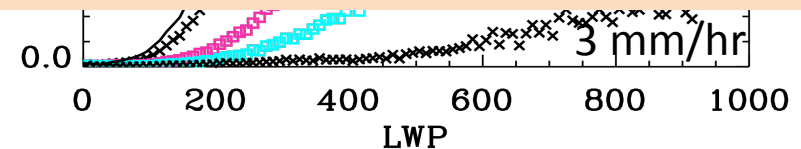


coalescence parameterizations  $\text{Rain} \sim (1 - \exp(\text{LWC}/\tau))^2$



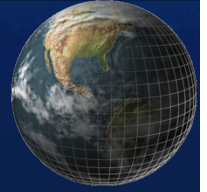
A consistent picture has emerged on the topic of (warm) rain and its representation in models- models make rain too rapidly that falls out too readily with the end result that rain occurs too frequently (and too lightly) compared to the real world. Thus the entire character of model precipitation differs from reality. The consequences of these biases to other aspects of the earth systems are profound

CRM





# Summary

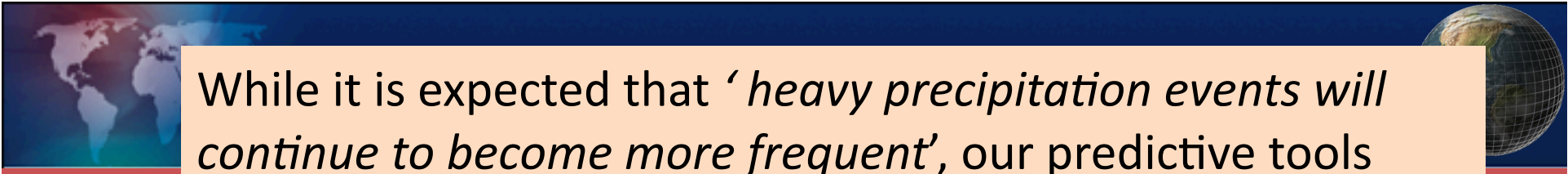


With global warming we expect an increase in atmospheric water vapor  $\sim 7\%/K$  – global measurements support this expected increase

This lower level water vapor drives a water vapor feedback involving important increases in DLR which is amplified/suppressed by UT moisture feedbacks

This lower level vapor change drives changes in radiative cooling that in turn control the rate of increases of global precipitation but at a rate significantly less than water vapor ( $\sim 2\%/K$ ) – global observations show little or no change in global precipitation over the last 20 years.

(High) Cloud radiative feedbacks can potentially influence this rate of change – apparently suppressing the global precipitation increase.



While it is expected that '*heavy precipitation events will continue to become more frequent*', our predictive tools (either climate or NWP models) contain major biases that are symptomatic of unrealistic rain physics.

While I believe the changes predicted in the FAR are the most likely scenario in a warming world, and further that these are likely to occur primarily driven by changes in the large scale atmospheric flows (hypothesis), we have to conclude our models have little or no ability to make credible projections about the changing character of rain and cannot conclusively test this hypothesis.

This model bias isn't merely solved by higher resolution of models – to the contrary, there are fundamental flaws in the way rain is triggered in models on all scales. The consequence to other aspects of the Earth system model is profound.



Backup



The strength of the greenhouse effect is proportional to the difference between  $T_s$  and  $T_p$



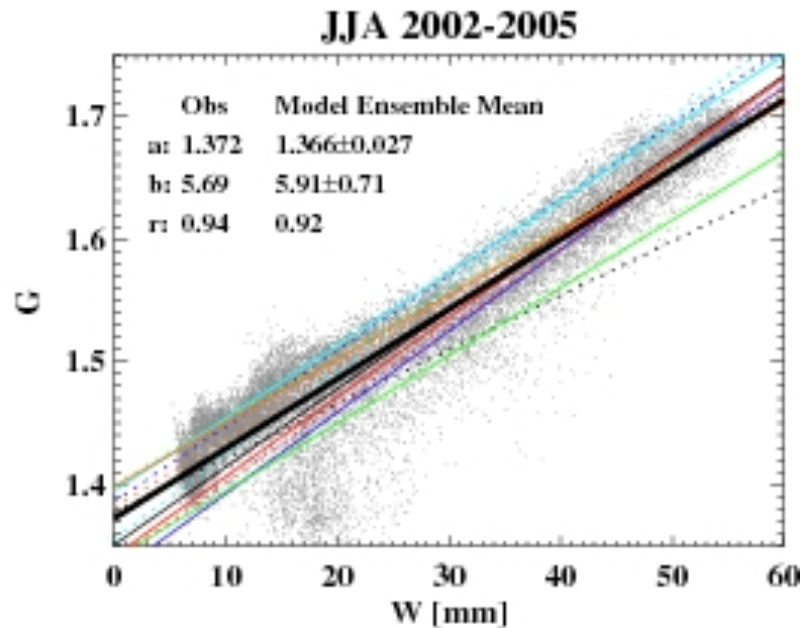
Radiative equilibrium theory

SST

$$G = \frac{\sigma T_s^4}{\sigma T_p^4} \approx a + bW$$

Satellite observations of clear-sky OLR

Satellite observations of water vapor over oceans



ERBE/CERES =clear-sky OLR

SSMI+TMI+AMSRE =W

Reynolds OI =SSTs

IPCC FAR SRES model simulations,  
yrs 2002-2005

Relation, derived from global distributions of SST,OLR and W -  
correlation  $r \sim 0.94$



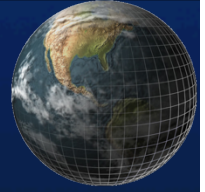
$$G = G(c, W)$$

$$\Delta T \sim \frac{1}{1-f} \Delta T_0$$

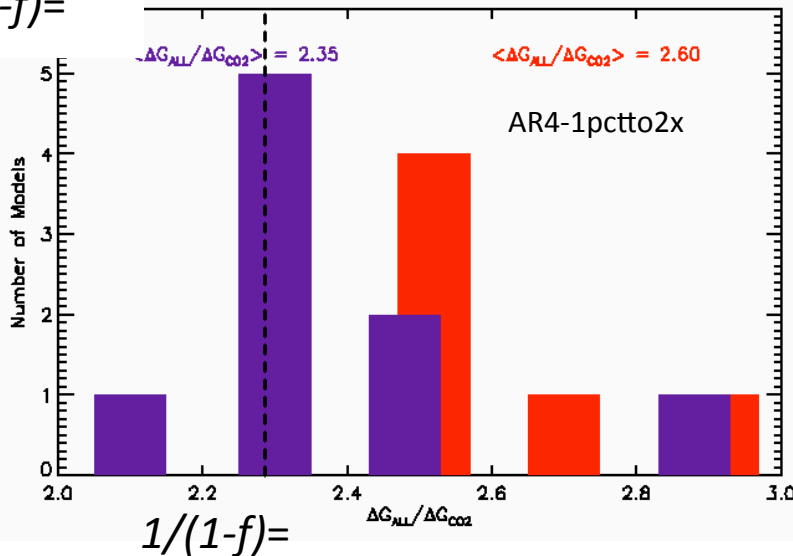
$$\frac{1}{1-f} \sim \frac{\Delta G}{\Delta G_0} \quad \text{Positive if } > 1$$

$\Delta G_0 \rightarrow$  **TOA CO2 forcing**

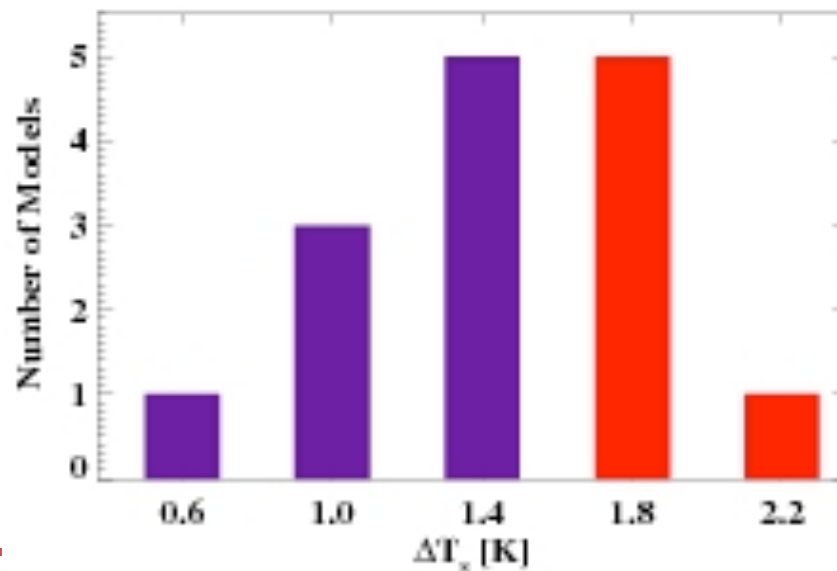
**$[\sim 2.5 \text{ Wm}^{-2} \text{ (2000 - 2070), } 0.38 \text{ Wm}^{-2} \text{ (1988 - 2005)}]$**



$$1/(1-f)=$$



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- From observation,  $f=2.3\pm1.0$  - so the results suggest that the water vapor feedback is (strongly) positive

- Stronger feedback exists in models with amplified UT moistening (=UT warming)

- The warmest models are those that exhibit greater UT moistening

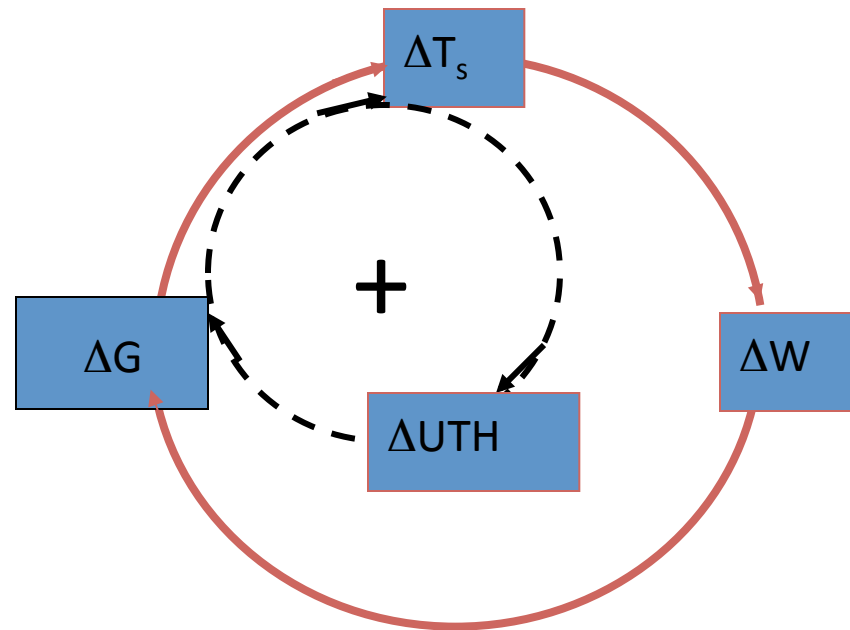
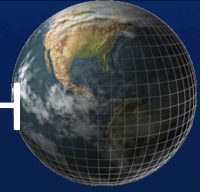


$\Delta RH_{500} > 23\%$



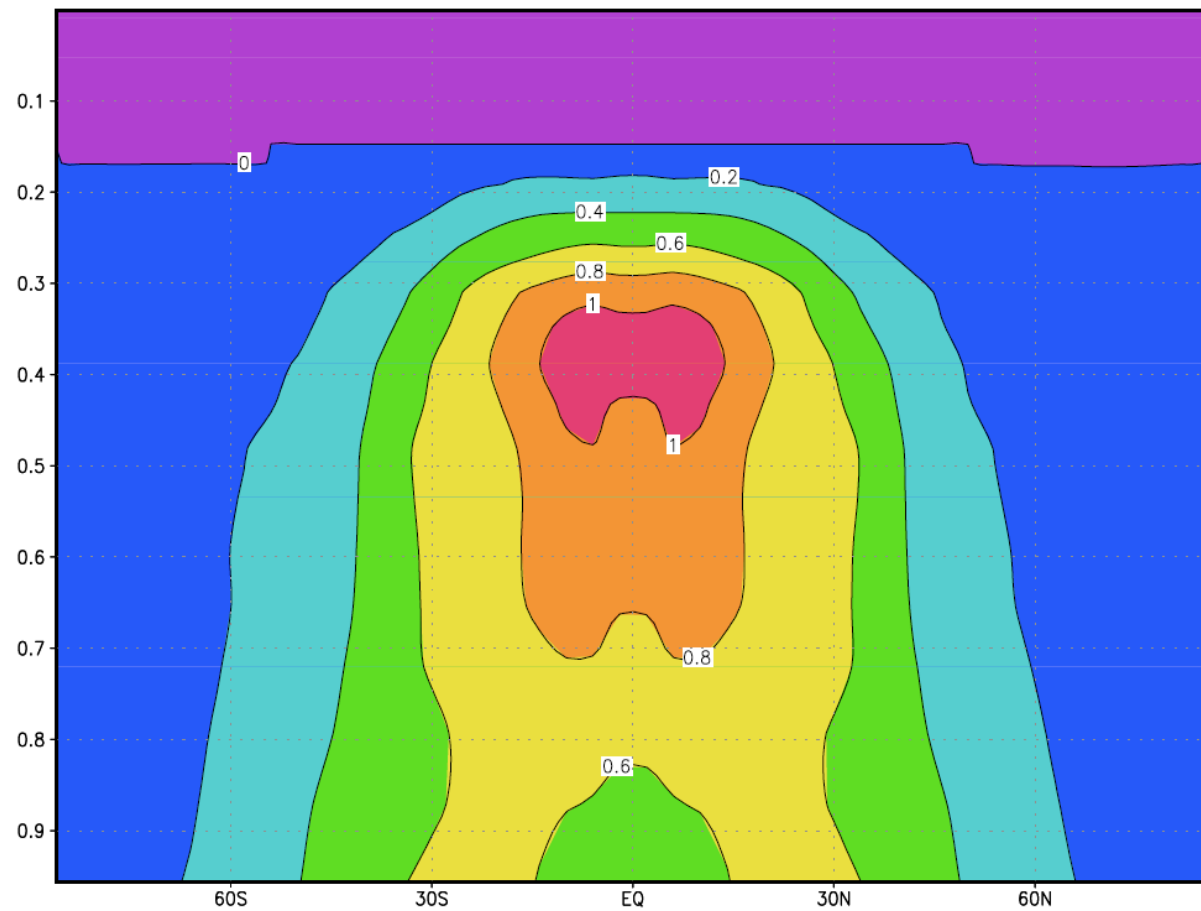
$\Delta RH_{500} < 23\%$

# The wv feedback loop and the amplifying effect of UTH





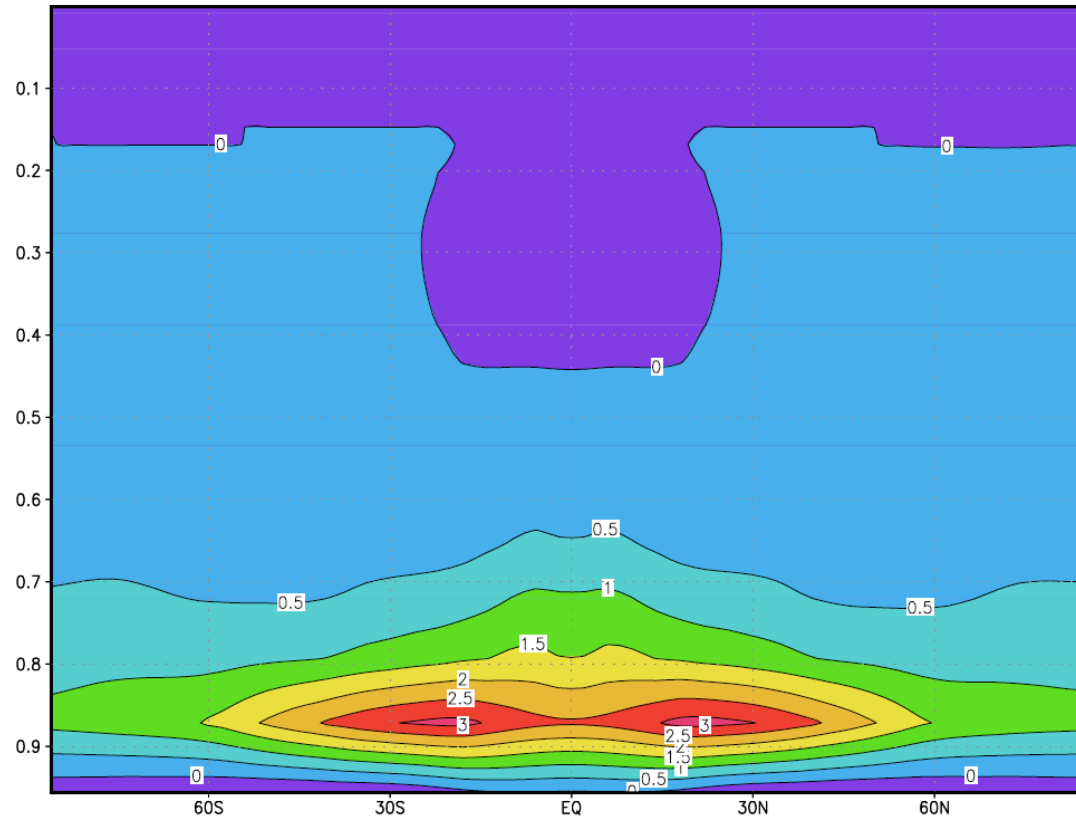
contribution to decrease in U\_Rad at TOA



$$\frac{\Delta OLR}{\Delta q(z)}$$



contribution to increase  $D_{\text{rad}}$  at surface ( $\text{W}/\text{m}^2/100\text{hPa}$ )



$$\frac{\Delta DLR}{\Delta q(z)}$$